

## PROGRAM OPTIMIZATION

### Inventors:

Xinliang David Li; Muralitharan Vijayasundaram; Dmitry Mikulin; and  
Shin-Ming Liu

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## BACKGROUND OF THE INVENTION

### Field of the Invention

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The present invention relates generally to computer software.

### Description of the Background Art

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Whole program analysis enables aggressive compiler optimizations and improvements to a software program's runtime performance. The ultimate goal of whole program analysis is to analyze source code for substantially the entire program during the compilation phase to obtain an optimized compilation. One difficulty with whole program analysis is that the compiler normally does not have access to the source code of the entire program and so does not have access to all the information it needs for optimization. Instead, the compiler typically only has access to source code provided to the compiler by the programmer (user), but not access to the source code for previously compiled object files of a library or separate load module. Without access to this information, the compiler cannot fully identify all the different relationships between the various portions of the whole program.

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Obstacles to the widespread use and adoption of whole program analysis include the following. First, many software applications are developed using third party shared libraries for which source code is unavailable. Second, some software applications are developed using previously compiled modules from a third party, and source code for these modules is typically unavailable. Third, even if a software program is being developed without third party shared libraries or modules, a programmer often chooses to partition the sources and build them into shared libraries.

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## SUMMARY

One embodiment of the invention relates to a method of generating a software program executable binary file. A first file including source code  
5 therein is accessed. A second file including object code therein and further including object file summary information is accessed. The executable binary file is generated from at least the first and second files. The object file summary information is used in optimizing the executable binary file generated.

Another embodiment of the invention pertains to a system for  
10 generating a software program executable file. The system includes a source file for the program, an object file including object file summary information, and a translator configured to access at least the source and object files and to generate the executable file of the program therefrom. The object file summary information is used in optimizing the executable file generated.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram depicting a system for generating a software program executable file in accordance with an embodiment of the  
20 invention.

FIG. 2 is a schematic diagram depicting an exemplary computing system on which the translator shown in FIG. 1 may be executed.

FIG. 3 is a flow chart depicting a method of generating a software program executable binary file in accordance with an embodiment of the  
25 invention.

FIGS. 4 through 8 provide source code routines used as examples in the detailed description.

## DETAILED DESCRIPTION

FIG. 1 is a schematic diagram depicting a system **100** for generating a software program executable file in accordance with an

embodiment of the invention. The system **100** includes a translator **102** that is used to translate and optimize a source program **104** into executable binary code. The translator **102** includes a compiler **106**, a linker **108**, and a feedback provider **110**.

5           The compiler **106** is configured to translate source files **112** of the source program **104** into intermediate objects and object files. The linker **108** is configured to link the various object files, including those compiled by the compiler, into the executable program. The linker **108** may also access and use code and other information in various files, for example, program libraries **118**  
10       and real objects **124**. The program libraries **118** may include archive libraries **120** and shared libraries **122**.

          As depicted in FIG. 1, the compiler **106** may include various modules. In accordance with an embodiment of the invention, the compiler **106** includes a points-to analyzer **132**. In accordance with another embodiment of the  
15       invention, the compiler **106** includes a modification/reference analyzer **134**. The operation of these modules is described further below. As further shown in FIG. 1, the system **100** also includes a linker global symbol table **130**. This table is created and maintained by the linker **108** and, as described further below, may be used to provide various information pertinent to program optimization.

20           The feedback provider **110** provides a feedback communications channel between the linker **108** and the compiler **106**. In an embodiment, the feedback provider **110** comprises a dynamically loadable library (DLL) that contains the various application programming interfaces (APIs) used by the compiler **106** to access the linker **108** and by the linker **108** to access the  
25       compiler **106**.

          FIG. 2 is a schematic diagram depicting an exemplary computing system **200** on which the translator **102** shown in FIG. 1 may be executed. For example, the computing system **200** may comprise a workstation, desktop computer, portable computer, dedicated server computer, multiprocessor  
30       computing device, or other type of computing system. The computing system **200** may include a processing device **202**, a memory system **204**, and various other components. The processing device **202** typically comprises one or more microprocessors. The memory system **204** may comprise various forms of

memory and may hold an operating system **216**, as well as the translator **102** and the source program **104** to be translated. These various other components may include, for example, user interface device(s) **206**, a display device **208**, other input/output devices **210**, network interface device(s) **212**, and other components. A communications system **214** (for example, comprising one or more communications buses) is used to interface between the various components. While FIG. 2 shows typical components and a generalized configuration for such a computing system **200**, the details for such a system will vary according to the implementation.

FIG. 3 is a flow chart depicting a method **300** of generating a software program executable binary file in accordance with an embodiment of the invention. The method **300** involves various steps, as discussed below. Variations of this method **300** may also be implemented in accordance with other embodiments of the invention.

The compiler **106** accesses and analyzes, in block **301**, the source files **112** that have been provided to the compiler **106** for compilation. Through the analysis, the compiler **106** processes and translates, in block **302**, the source files **112** into intermediate objects.

The intermediate objects are provided, in block **304**, to the linker **108**. The linker analyzes, in block **306**, the "whole" program, including accessing various components, such as the intermediate objects, libraries **118**, and real objects **124**, to collect information about the program that will be provided to the compiler **106** so that the program may be optimized in some manner during the final compilation process.

The linker **108** returns, in block **308**, the intermediate objects to the compiler **106**, and feedback is provided, in block **310**, to the compiler **106** via the feedback provider **110**. The feedback includes information determined by the linker **108** during the aforementioned analysis in block **306**. Once this feedback has been provided to the compiler **106**, the compiler **106** completes the translation of the intermediate objects to generate, in block **312**, real objects. The real objects are subsequently linked together, in block **314**, by the linker **108** to produce an executable binary program.

In accordance with an embodiment of the present invention, the optimization of the executable program is improved by way of utilizing object file summary information. Object files, such as the real objects **124** and the object files from the libraries **118**, are configured to include this object file summary information, in addition to the object code therein. The object file summary information is described in further detail below.

In accordance with an embodiment of the present invention, the points-to analyzer **132** of the compiler **106** uses the object file summary information during the whole program type analysis in block **306**. As discussed further below, the object file summary information is used by the points-to analyzer **132** in order to disambiguate memory accesses otherwise considered aliased.

In accordance with another embodiment of the present invention, the object file summary information is used by the modification/reference (mod/ref) analyzer **134** of the compiler **106** during the whole program type analysis in block **306**. As discussed further below, the object file summary information is used by the mod/ref analyzer **134** to determine variables modified by and referenced by function calls.

Before proceeding, a few terms are now discussed. A module is a unit of compilation. A module physically corresponds to a file containing a collection of function and data definitions. A module may be in three different forms. First, a module may be in source file form, i.e. in the form of source languages. Second, a module may be in intermediate form. The intermediate form represents the module in a form that is suitable for program analysis and optimization. Third, a module may be in object file form. The object file contains machine code that may be executed. A shared library is a collection of functions and/or procedures that can be shared by multiple executables. A linker may create a shared library using one or more object files. A shared library is sometimes called a load module. An application program may depend on one or more shared libraries to run.

As described above in the background, there are difficulties in using whole program analysis to effectively optimize a program being compiled when the program utilizes object files, archive libraries, and/or shared libraries.

An embodiment of the present invention provides a method and system to improve optimization achievable by whole program analysis.

The following describes in further detail a method and system that allow a translator to perform points-to analysis and mod/ref analysis in the presence of object files, archive libraries, and shared libraries. Points-to analysis and mod/ref analysis are two types of whole program analysis. Points-to analysis improves optimization by disambiguating memory accesses otherwise considered aliased. Mod/ref analysis improves optimization by determining which variables are modified by and referenced by function calls in the object code.

The general problem posed is now described using an example. Suppose there are five modules. Three of these modules are in source form (or in an intermediate form), while the other two are in object form. For example, the modules in source form may be named "1.c", "2.c", and "3.c" (where ".c" indicates a source file), and those in object form may be named "4.o" and "5.o" (where ".o" indicates an object file).

The executable file for the program may be built using different build scenarios. For example, in a first build scenario, 1.c, 2.c, and 3.c are compiled, then they are linked with 4.o and 5.o. In a second build scenario, 4.o and 5.o are linked into a shared library (for example, "libt.so"), then 1.c, 2.c, and 3.c are compiled and linked with the shared library. In either of the above scenarios, it is desirable to perform whole program analysis when compiling 1.c, 2.c, and 3.c, but the program information for modules 4 and 5 are not available because they have been precompiled to object form.

One aspect of the present invention relates to solving the above-discussed problem. In accordance with an embodiment of the invention, information needed to perform certain types of whole program analysis are determined and saved into the object files. This information may be thought of as being equivalent to having the whole source for those modules available with respect to those types of analysis. We call this information "object file summary information" (OFSI) to distinguish this type of summary data from the summary data stored in intermediate representation (IR) files which are used for the purpose of speeding up the compile time.

OFSI may be included in both standalone object files, and those that are linked into libraries. When objects are linked into shared libraries, the OFSI for the contributing object files may be merged. Later, when performing the applicable whole program analysis, the compiler may ask the linker to feed  
 5 back the OFSI stored in the standalone object file or shared library through a callback mechanism.

#### OFSI and Points-To Analysis

In accordance with an embodiment of the invention, the object file summary information (OFSI) is used in performing a "points-to" analysis so as to  
 10 disambiguate memory accesses otherwise considered aliased. Points-to analysis determines the points-to relations of memory locations or memory alias information. The results of the points-to analysis may be used by a compiler to disambiguate memory accesses that are otherwise considered aliased. The improved alias information provided by points-to analysis advantageously  
 15 benefits optimization of the compiled code, including scheduling performed by the compiler backend.

FIG. 4 show source code for two example routines named "bar" and "foo". These two routines are used to give a concrete example for our discussion of the points-to analysis aspect of the present invention.

20 Conventionally, the function "bar" would be defined in a module in object form without OFSI. Without the OFSI, the compiler cannot determine, after the call to bar in "foo", whether or not indirect memory accesses by way of "fp1" and "fp2" alias with "g". The compiler will instead work on the assumption that fp1 and fp2 may point to anything, including g.

25 In accordance with an embodiment of the invention, OFSI for points-to analysis is included in the object file for bar. Using the OFSI, the compiler is able to apply points-to analysis to determine that the indirect accesses via fp2 do not alias with g, but that the indirect accesses via fp1 must alias with g. With this alias information determined, the constant definition of  
 30 "g=1" may be advantageously propagated by the compiler to the use of g in the loop within foo. The compiler may also advantageously determine that the assignment "g=1" is no longer needed after the propagation, and so the use of "g" in the return statement may be replaced simply with "20". In addition, the

compiler is also then free to reorder the instructions labeled (1) and (2) in FIG. 4. Hence, after the optimization, “foo” may be, for example, effectively changed to be as shown in FIG. 5.

An embodiment of the OFSI for points-to analysis is now  
 5 described. This embodiment implements the OFSI in a generic-like form so that it is substantially independent of the specific points-to algorithm used and independent of the specific compiler that consumes the information. In accordance with this embodiment, the OFSI includes an extension to the linker symbol table, summary intermediate representations (SIRs) that are stored in the  
 10 object files (and shared libraries), and control data structures in the object files (and shared libraries). The SIRs may also be referred to as per-procedure summary data.

The linker symbol table exists for relocatable objects and shared  
 libraries (if not stripped). There is one linker symbol table per module or per  
 15 shared library. The table defines the global context for the summary data. Each linker symbol table entry has a unique index, here referred to as a linker identifier (LI\_ID).

In accordance with this embodiment, the extension to the linker  
 symbol table comprises a boolean flag “doesNotExposeAddress” added for each  
 20 procedure identified therein. If the procedure does not expose addresses of any memory location, this flag is set to true for that procedure. A procedure does not expose addresses of any memory location when it does not save the address into any memory location accessible outside of the procedure. For all such  
 procedures with the flag set to true, no additional OFSI is needed for the purpose  
 25 of points-to analysis.

In accordance with this embodiment, the SIR includes the bulk of  
 the OFSI and is organized per procedure for procedures defined in the library or  
 object file. The SIR includes a summary symbol table per procedure and a list  
 including exposed pointer assignments (SIR assignments).

30 The exposed pointer assignments comprise the pointer assignments that may affect the pointer values visible to the caller of the procedure. Assignments to non-exposed local variable of the procedure can be safe to ignore after propagating the variable’s value to all uses of the variable.



For example, consider the example source code shown in FIG. 6. The assignment labeled (1) is non-exposed and so need not be represented in the SIR. However, the assignment labeled (2) is exposed and so is to be represented in the SIR (as  $gp = f$ ).

5           As a further detail, consider local variables whose addresses are exposed to other global variables (either directly or indirectly). These exposed local variables may also be safely ignored (i.e. not represented in the SIR) if all callees called by the current procedure are also defined in the same library.

Each symbol in the summary symbol table has an associated  
10 identifier herein referred to as the SYMID. The SYMID is referenced by SIR assignments (SIR operators). Note that the use of SYMID in the assignments does not require linker fixup when object files are linked into shared libraries.

In accordance with an embodiment, the summary symbol table of the SIR includes data relating to the following: a) global and static symbols  
15 accessed in the procedure; b) formal parameters (formal symbols) of the procedure; c) the function return location for the procedure; and d) other procedures called by this procedure. The global/static symbol entry includes the LI\_ID of the entry in the above-discussed linker symbol table. The data relating to the formal parameters includes the positions of the formal parameters. An  
20 object relocation type is used that is system specific.

For example, the SIR assignments may be of the following format: <LHS\_EXP, RHS\_EXP, <offset>>, where LHS\_EXP refers to the left hand side of the expression and RHS\_EXP refers to the right hand side of the expression. The offset is optional and may default to zero when omitted. Various operators  
25 may be defined and used in the SIR assignments. In accordance with an embodiment of the invention, these operators include deref, off\_adjust, address\_of, merge, join, call, ical, and no\_op operators.

The deref operator comprises an operator for memory referencing. In this implementation, the kind of access (read or write) may be implied by the  
30 context of the operator and need not be represented explicitly. The deref operator may take the form of deref (SYMID | address\_expression, <offset>). In this form, the deref operator takes an expression or SYMID as the first operand and an optional offset field. When the offset is omitted, it is assumed to be zero.

The following are example expressions using the deref operator.

First, consider a direct access to variable "x". This may be represented by deref (x). Second, consider a direct access of field "fd" (at offset 4) of variable "y".

This may be represented by deref (y,4). Third, consider an indirect access via the pointer \*x. This may be represented by deref (deref (x)). Fourth, consider an indirect access of a field fd (at offset 4) of a location pointed to by pointer z. This may be represented by deref (deref(z), 4). Alternatively, using the off\_adjust operator discussed below, this may be represented by deref (off\_adjust (deref(z), 4)).

The off\_adjust operator may be used to adjust the address expression by a certain (non-zero) amount of offset in bytes. The off\_adjust operator may take a form that uses two operands, wherein a first operand comprises the expression, and a second operand comprises the offset value. The offset may be unknown.

The following discusses an example of a SIR assignment using the deref and off\_adjust operators. Consider the expression  $x = (\text{char}^*) \&z \rightarrow \text{fd} + 12$ . The corresponding SIR assignment to represent that expression may comprise

$$\langle \text{deref}(x), \text{off\_adjust}(\text{deref}(z), 16) \rangle$$

wherein 16 is the folded value of 4 (the offset of field "fd") plus 12. The above expression may be equivalently represented as

$$\langle \text{deref}(x), \text{deref}(z), 16 \rangle$$

which is a more efficient form.

The address\_of operator comprises the operator that is used to take the address of a variable or function. For example, the expression  $z = \&y$  may be represented by the SIR assignment  $\langle \text{deref}(z), \text{address\_of}(y) \rangle$ . As another example, the expression  $x = \&y.\text{fd}$  may be represented by the assignment  $\langle \text{deref}(x), \text{off\_adjust}(\text{address\_of}(y), 4) \rangle$ . Note that deref (address\_of (x)) is equivalent to deref (x).

The merge operator comprises the operator used to merge pointer values from different control flow paths. The merge operator is used for copy propagating local variable values to global variables. Consider the example source code included in FIG. 7. After copy propagation, the expression labeled 5 (1) in FIG. 7 may be represented by the following SIR assignment:

`<deref(gp), merge(deref(deref(f),4), off_adjust (address_of(g), 12))>`

The join operator relates to pointer assignments. Pointer 10 assignments in the right hand side of expressions in source code are usually in the form of `base_address + offset`. However, in many cases, the compiler cannot determine which component value is the base address and which one is the offset. This difficulty is often due to use of pointer values as integer types. In such a case, the compiler generally makes the conservative assumptions that 15 each component value may potentially be the base address, and that the offset is compile time unknown.

For example, consider the expression `x = a + b + c`, where all of the variables are integers. It is possible that "a" is the base address, and that `b+c` is the offset. It is also possible that "b" is the base address, or that "c" is the 20 base address. Hence, one way to represent this is to split the SIR assignment into the following three assignments to represent the potential pointer effects.

`x = a + unknown_offset`  
`y = a + unknown_offset`  
 25 `z = a + unknown_offset`

However, the above representation requires more space and is inefficient. To facilitate the assignment in such situations, the join operator may be utilized. Using the join operator, the expression `x = a + b + c` may be represented using 30 the following assignment.

`<deref(x), join (deref(a), deref(b), deref(c))>`

Note that the join operator implies off\_adjust (... , unknown\_offset), so join (...) is equivalent to off\_adjust (join(...), unknown\_offset).

The call operator comprises the operator used to represent direct procedure calls. The call operator takes an arbitrary number of operands. The first operand is the SIR SYMID of the target function. The rest of the operands are argument expressions.

The ical operator comprises the operator used to represent indirect procedure calls. The ical operator also takes an arbitrary number of operands. The first operand is the expression that produces the function pointer. The rest of the operands are argument expressions.

The no\_op operator comprises the "no operation" operator that may be used to discard values. For example, if a call does not have a return value, or if the return value is not used, the no\_op operator may be used in the LHS\_EXP. The no\_op operator does not have any operand. Consider the example source code in FIG. 5. The expressions labeled (1), (2), and (3) are representable with the following assignments:

```
<deref(gp), call(malloc), deref(i)>
<no_op(), call(bar)>
```

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Now we discuss the control data structures. A control data structure is included in the summary data in the object files and shared libraries. The compiler uses the control data structure to iterate through all of the procedures therein. In one embodiment, the control data structure is implemented by having a link field in the SIR data block for each procedure. This link field points to the SIR block of the next procedure. In another embodiment, the control data structure is implemented by having a separate table containing links to the SIR block of each procedure. With either implementation, when object files are linked into shared libraries, the linker adjusts the link fields accordingly.

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#### Mod-Ref Analysis

In accordance with another embodiment of the invention, the object file summary information (OFSI) is used in performing a "modification/reference"

(mod-ref) analysis. The mod-ref analysis determines variables modified by and referenced by function calls. The results of the mod-ref analysis may be used advantageously by the compiler to improve optimization of the compiled code.

5 The objective of mod-ref analysis comprises finding out the call-side effects of the function call. In other words, mod-ref analysis determines which variables are modified by the call, and which variables are referenced by the call, if any. In order to compute the mod-ref sets for a procedure, the compiler determines the following: a) global and static ("non-local") symbols that are directly modified or referenced ("mod-ref'd") in the procedure; b) the mod-ref  
10 sets of calls invoked in this procedure; and c) the points-to analysis results (discussed above).

Most of the information needed to perform the mod-ref analysis is already in the OFSI for the points-to analysis (discussed above). The following additions to the OFSI are used to perform the mod-ref analysis.

15 a) Additional summary bits (flags) are to be added as a further extension to the linker symbol table. In one embodiment, these bits may comprise the following flags. A first flag indicates that the procedure does not modify global or static variables. A second flag indicates that the procedure does not reference global or static variables. A third flag indicates that the  
20 procedure does not modify global or static variables directly (excluding callees). A fourth flag indicates that the procedure does not reference global or static variables directly (excluding callees).

b) Additional per-procedure summary data is also included. The additional summary data may be represented as a linked list of entries. Each  
25 entry corresponds to a symbol directly modified or referenced in the procedure. The entry includes the following information. First, the LI\_ID of the symbol. Second, flags indicating whether the symbol was modified or referenced.

In the above description, numerous specific details are given to provide a thorough understanding of embodiments of the invention. However,  
30 the above description of illustrated embodiments of the invention is not intended to be exhaustive or to limit the invention to the precise forms disclosed. One skilled in the relevant art will recognize that the invention can be practiced without one or more of the specific details, or with other methods, components,

etc. In other instances, well-known structures or operations are not shown or described in detail to avoid obscuring aspects of the invention. While specific embodiments of, and examples for, the invention are described herein for illustrative purposes, various equivalent modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize.

These modifications can be made to the invention in light of the above detailed description. The terms used in the following claims should not be construed to limit the invention to the specific embodiments disclosed in the specification and the claims. Rather, the scope of the invention is to be determined by the following claims, which are to be construed in accordance with established doctrines of claim interpretation.